

# A method for determining the attitude of a small unmanned aerial vehicle using sensor error information and a neural network

David Kofi Oppong<sup>a</sup>, Joshua Ampofo<sup>a</sup>, Eunice Akyereko Adjei<sup>a</sup>, Anthony Agyei-Agyemang<sup>a</sup>, Kwasi Kete Bofah<sup>a</sup>, God'sable Sitsofe<sup>a</sup>, Koku Aidam<sup>a</sup>, Mary Korkor Teye<sup>a</sup>, Charulatha Siva<sup>b</sup> & Samuel Vivek Williams<sup>c</sup>

<sup>a</sup>Department of Mechanical Engineering, Kwame Nkrumah University of Science and Technology, Kumasi Ghana

<sup>b</sup>Department of Aerospace Engineering, Hindustan Institute of Technology and Science, Rajiv Gandhi Salai, Chennai, India

<sup>c</sup>Department of Aeronautical Engineering, Mangalore Institute of Technology and Engineering, Mangaluru, Karnataka, India

Received: 11 April 2024; accepted: 30 October 2024

The study has sought to identify a means for estimating the attitude of a small unmanned aerial vehicle by exploiting the fundamental operating principle of a neural network, using information about its micro-electro-mechanical systems sensors' error properties. Individual attitude solutions have been derived from the accelerometer, gyroscope and magnetometer using traditional techniques. These solutions have been then fused together using a weighting strategy that ensures that each sensor's error is accounted for. The developed algorithm has drawn upon knowledge from statistical noise parameter estimation and voting strategies applied in redundant aircraft systems to ensure that the system output closely matches the platform's actual attitude. Experiments that have been carried out to determine the efficacy of the developed algorithm using data from real world flights have shown that the algorithm has improved accuracy compared to the individual sensor solutions, with root-mean-square-error of below  $1^0$  in several situations.

**Keywords:** Attitude determination, Euler angles, Neural networks, Unmanned aerial vehicles (UAV)

## 1 Introduction

Small unmanned aerial vehicles (UAVs) continue to be used to perform a host of functions with applications in agriculture, security and emergency response, surveying, photography and recreation<sup>1</sup>. They are usually controlled autonomously or by a remote pilot, who is usually within sight of the UAV<sup>2</sup>. In order to change the flight path of the aircraft, it is necessary to change its attitude<sup>3,4</sup>. The attitude solution also serves as an input to the aircraft's autopilot<sup>5</sup>. Several approaches have been used in the past to compute the UAV's attitude, making use of different sensors onboard the vehicle in various ways. In this paper, we present an approach that draws upon the fundamental operating principle of a neural network, using the magnetometer, accelerometer, gyroscope and global navigation satellite systems (GNSS) sensors onboard the aircraft to derive its attitude.

## 2 Materials and Methods

The aircraft attitude is first calculated using the sensors' outputs individually. Following this, the individual attitude solutions are combined statistically.

### 2.1 Individual Sensor Attitude Solutions

#### 2.1.1 Accelerometer

An accelerometer measures the specific force of the vehicle relative to inertial space in body coordinates<sup>6</sup>. The principle of deriving vehicle attitude from the accelerometer lies in obtaining the quaternion or rotation matrix that transforms its measurements to a reference coordinate system such as the Earth Centered Earth Fixed (ECEF) system. A GNSS sensor provides velocity estimates which may be differentiated using, for example, Al-Alaoui's filter<sup>7</sup> to provide the reference acceleration. The position estimate from the GNSS sensor also aids determination of the value of acceleration due to gravity. Having these measurements, it is possible to determine the aircraft's attitude using the equation:

$$\dot{V} = f - 2\omega_{ie} \times V + g \quad \dots (1)$$

where,  $V$  stands for velocity,  $\omega_{ie}$  is the earth's rotation rate and  $g$  is the acceleration due to gravity, all expressed in ECEF coordinates.

The quaternion that transforms the specific force (the  $f$ -term) from ECEF coordinates to (North-East-Down) local navigation coordinates is

\*Corresponding author (E-mail: dkoppong55@gmail.com)

determined from the position estimate,  $[longitude(l), latitude(\phi), altitude(h)]^8$  provided by the GNSS sensor, using the equations.:

$$q = \begin{bmatrix} \cos \frac{l}{2} \cdot \cos \left( \frac{\phi}{2} + 45^\circ \right) \\ \sin \frac{l}{2} \cdot \sin \left( \frac{\phi}{2} + 45^\circ \right) \\ -\cos \frac{l}{2} \cdot \sin \left( \frac{\phi}{2} + 45^\circ \right) \\ \sin \frac{l}{2} \cdot \cos \left( \frac{\phi}{2} + 45^\circ \right) \end{bmatrix} \dots (2)$$

It remains therefore to solve for the quaternion that performs the transformation from local navigation coordinates to body coordinates. This provides the attitude solution.

2.1.2 Magnetometer

The magnetometer measures the components of the earth’s magnetic field in body coordinates. Knowing the reference magnetic field in local navigational coordinates from a model such as the *World Magnetic Model*<sup>9</sup>, it remains to determine the quaternion that transforms between the two coordinates. This provides the attitude solution.

2.1.3 Gyroscope

A three-axis gyroscope provides measurements of the aircraft’s angular velocity,  $\Omega = \begin{bmatrix} p \\ q \\ r \end{bmatrix}$ . The attitude solution at any time may be obtained by integrating the attitude rates of the aircraft derived from the quaternion state equations, given below, knowing the initial state:

$$\dot{q} = \begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -p & -q & -r \\ p & 0 & r & -q \\ q & -r & 0 & p \\ r & q & -p & 0 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \equiv \frac{1}{2} \Omega q \dots (3)$$

2.2 Quaternion Attitude to Euler Angles

The quaternion attitude solutions are used to derive the Euler angles (roll, pitch and yaw) using the following equations<sup>10</sup>.

$$\phi = \tan^{-1} \left( \frac{2(q_0 q_1 + q_2 q_3)}{1 - 2(q_2^2 + q_3^2)} \right) \dots (4)$$

$$\theta = \sin^{-1} (2(q_0 q_2 - q_1 q_3)) \dots (5)$$

$$\psi = \tan^{-1} \left( \frac{2(q_0 q_3 + q_1 q_2)}{1 - 2(q_2^2 + q_3^2)} \right) \dots (6)$$

2.3 Combined sensors attitude solution

The following weighting strategy<sup>11,12</sup> is applied to determine the integrated attitude solution from,

$$\theta = w_g \cdot \theta_g + w_a \cdot \theta_a + w_m \cdot \theta_m \dots (7)$$

The output of Equation 7 is fed to a low-pass filter using a cutoff frequency of 0.5 Hz, as suggested by Lötters<sup>13</sup>. An illustration of the approach is provided in Figure 1.

The weights are calculated using two pieces of information. First is the root-mean-square value of the sensor’s error spectrum<sup>14,15</sup>. This is taken as a constant sensor measurement that is randomly positive or negative and used to propagate an attitude estimate in time. The second is the deviation of the individual attitude solution from the mean value<sup>16</sup>. These two error attitudes are each normalized by dividing by their magnitude, and then combined by taking the 2-norm. Following this, a parameter,  $\alpha$ , is determined that minimizes the least-squares error between the combined (weighted) attitude solution and that derived from a traditional algorithm. Equation 8 to Equation 10 summarize the calculation of the weights;

$$w_{g,a,m} = \alpha \cdot \sqrt{w_1^2 + w_2^2} \dots (8)$$

$$w_1 = \frac{\delta \theta_i}{|\delta \theta_i|} \dots (9)$$

$$w_2 = \frac{\delta \psi_i}{|\delta \psi_i|} \dots (10)$$

where,  $\delta \theta$  is the error-spectrum RMS-derived roll, pitch or yaw attitude and  $\delta \psi$  is the roll, pitch or yaw deviation from the mean of all sensors’ solutions.

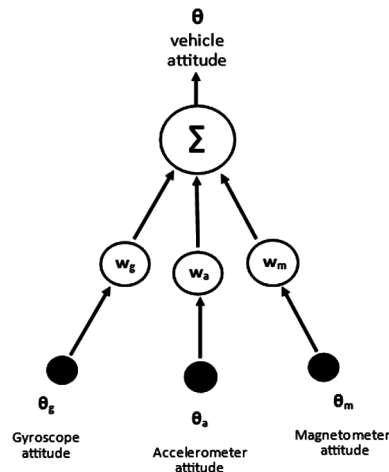


Fig. 1 — Model for combined-sensor attitude determination.

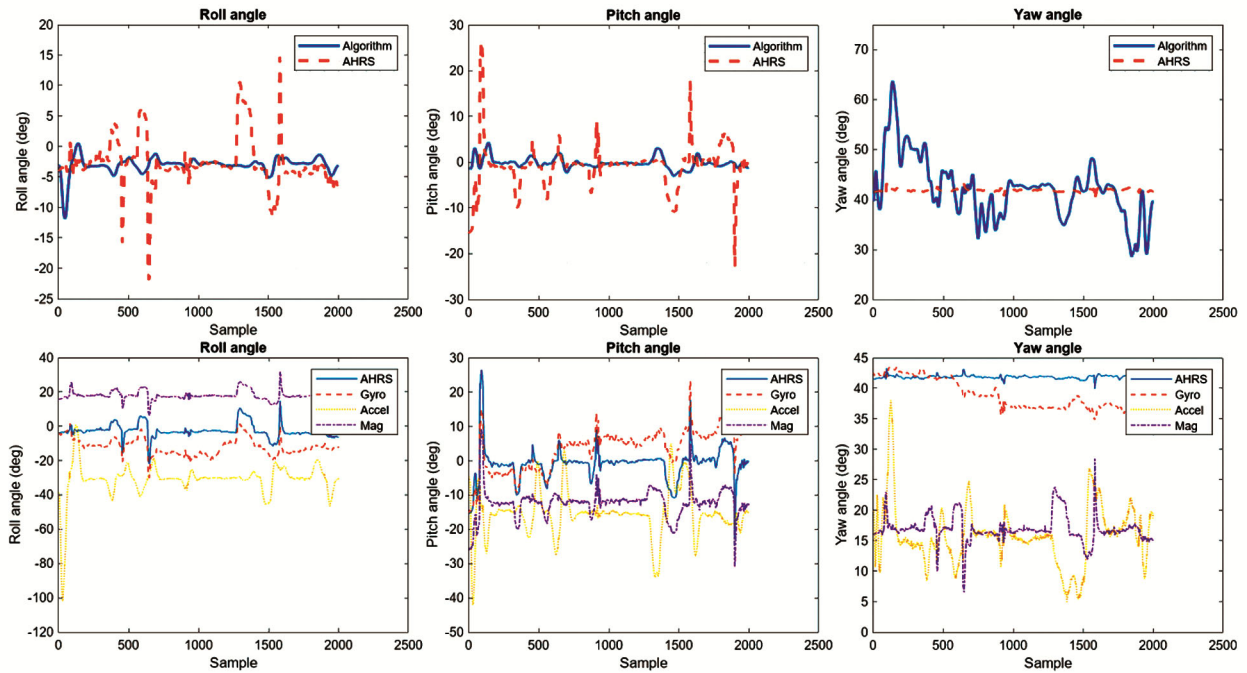


Fig. 2 — DJI Mavic 2 Pro attitude.

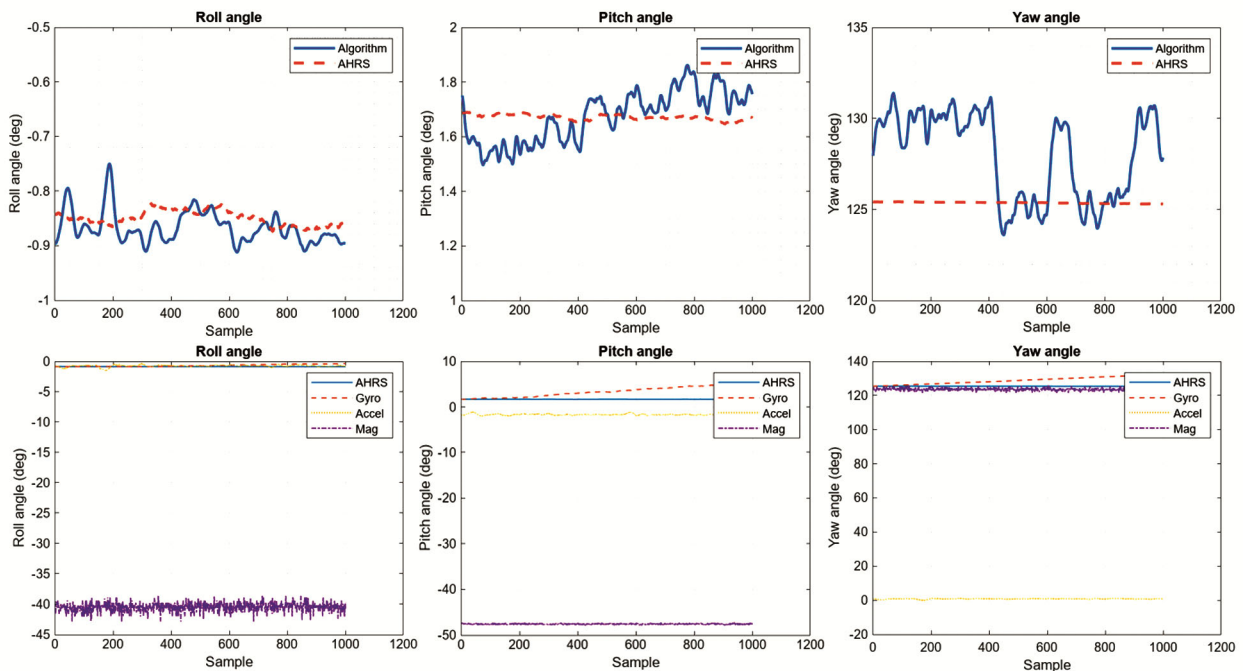


Fig. 3 — DJI Mavic Mini attitude.

### 3 Results and Discussion

Flight logs were collected from three UAV platforms: the DJI Mavic Mini, DJI Mavic 2 Pro and a fixed wing using an Ardupilot flight controller. The parameters retrieved from the logs included the three-axis accelerometer, magnetometer and gyroscope

readings, GPS position and the output of the UAV's attitude and heading reference system (AHRS) which also calculates the vehicle's attitude. The sensor readings were used to determine the drone's attitude, first individually, then combined using the developed algorithm. Figures 2, 3 & 4 illustrate the results,

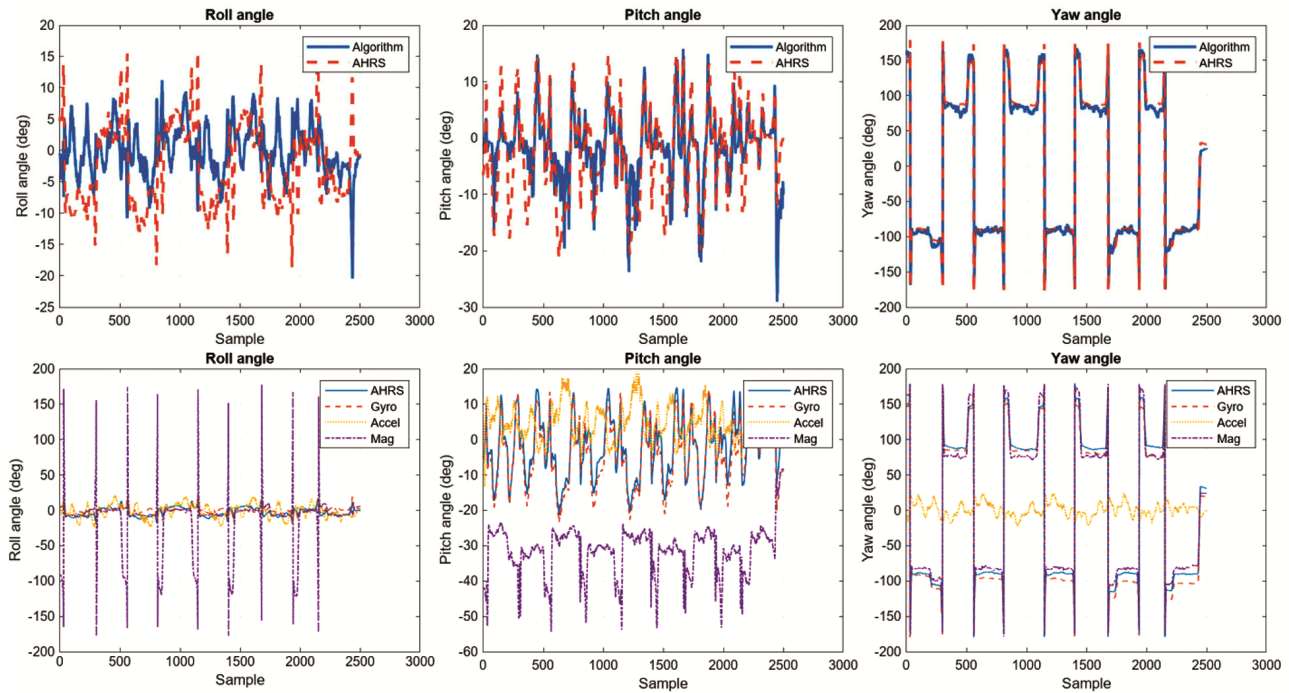


Fig. 4 — Arduplane attitude.

Table 1 — Performance of developed algorithm.

Aircraft	Sensor	RMS Error, relative to AHRS solution (deg)		
		Yaw	Pitch	Roll
DJI Mavic Mini	Algorithm	3.55	0.1	0.03
	Accelerometer	124.59	3.35	0.2
	Gyroscope	3.99	2.01	0.26
	Magnetometer	1.99	49.26	39.64
DJI Mavic 2 Pro	Algorithm	6.11	4.87	4.38
	Accelerometer	26.47	16.96	30.62
	Gyroscope	4.04	6.47	9.93
	Magnetometer	25.04	11.59	20.68
Arduplane	Algorithm	27.68	5.25	7.85
	Accelerometer	106.94	13.22	8.64
	Gyroscope	24.94	3.02	5.26
	Magnetometer	32.01	30.93	40.46

whiles Table 1 provides a summary of the performance of the algorithm.

It is evident from the figures and table above that the developed algorithm closely approximates that of the AHRS of the aircraft. The best performance is recorded along the roll channel of the DJI Mavic Mini, an RMSE of 0.03 degrees. The worst performance is along the yaw channel of the Arduplane, with an RMSE of 27.68 degrees. This large error is likely due to the flight path of the aircraft, which performed maneuvers that required a sharp change in heading, as shown in Figure 4.

Generally, the algorithm solution presents significant increases in accuracy compared with the individual sensor attitude solutions. For example, whereas the accelerometer of the DJI Mavic Mini deviated from the true value in excess of 100 degrees in yaw, the algorithm’s solution recorded an error of only 3.55 degrees, a two-orders-of-magnitude improvement. This trend is evidenced with most of the entries in Table 1.

#### 4 Conclusion

It has been shown that the error properties of the inertial sensors of a small UAV can be used in a

neural-networks configuration to compute its attitude. Experiments with three UAVs demonstrated that single-digit accuracy can be obtained using this technique.

### References

- 1 Al-Alaoui, M. A., 1993. Novel digital integrator and differentiator. *Electronics letters*, 29(4), pp. 376.
- 2 Blough, D. M. & Sullivan, G. F., 1990. *A comparison of voting strategies for fault-tolerant distributed systems*. s.l., s.n.
- 3 Chulliat, A. W. *et al.*, 2020. *The US/UK World Magnetic Model for 2020-2025*, s.l.: NOAA.
- 4 Collinson, R. P., 2023. *Introduction to avionics systems*. 4th ed. s.l.:Springer Nature.
- 5 Fahlstrom, P. G. & Gleason, T. J., 2012. *Introduction to UAV Systems*. 4th ed. Chichester: John Wiley & Sons Ltd..
- 6 Groves, P. D., 2013. *Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems*. Second ed. Boston: Artech House.
- 7 Gurney, K., 2005. *An introduction to neural networks*. London: Taylor & Francis.
- 8 Hearn, G. E. & Metcalfe, A. V., 1995. *Spectral analysis in engineering: concepts and cases*. Burlington: Elsevier Ltd..
- 9 Irvine, T., 2000. *Integration of the Power Spectral Density Function*. s.l.:Vibrationdata.
- 10 Kabamba, P. T. & Girard, A. R., 2014. *Fundamentals of aerospace navigation and guidance*. New York: Cambridge University Press.
- 11 Lötters, J. C. *et al.*, 1998. Procedure for in-use calibration of triaxial accelerometers in medical applications. *Sensors and Actuators A: Physical*, Volume 68(1–3), pp. 221.
- 12 McCulloch, W. S. & Pitts, W., 1943. A logical calculus of the ideas immanent in nervous activity. *The bulletin of mathematical biophysics*, Volume 5, pp. 115.
- 13 Quan, Q., 2017. *Introduction to to Multicopter Design and Control*. Singapore: Springer Nature.
- 14 Stevens, B. L., Lewis, F. L. & Johnson, E. N., 2016. *Aircraft Control and Simulation: Dynamics, Controls Design and Autonomous Systems*. Hoboken, New Jersey: John Wiley & Sons, Inc. .
- 15 Terwilliger, B., Ison, D., Robbins, J. & Vincenzi, D., 2017. *Small Unmanned Aircraft Systems Guide: Exploring Designs, Operations, Regulations, and Economics*. Newcastle: Aviation Supplies & Academics, Inc..
- 16 Titterton, D. H. & Weston, J. L., 2004. *Strapdown Inertial Navigation Technology*. Second ed. Stevenage and Reston: Institution of Electrical Engineers and The American Institute of Aeronautics and Astronautics.